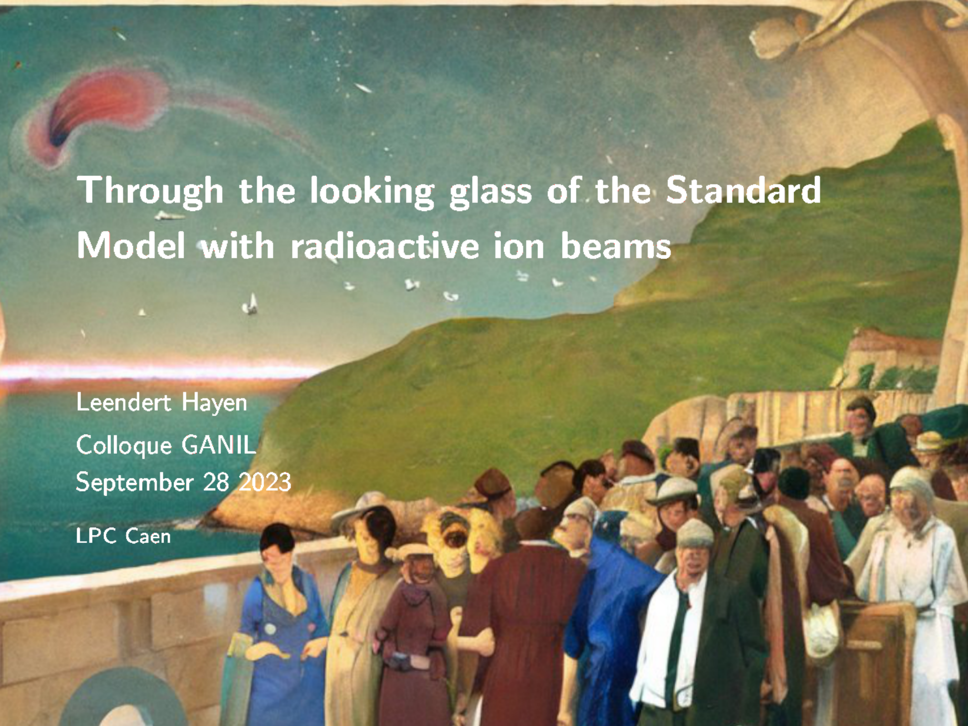
Through the looking glass of the Standard Model with radioactive ion beams



Leendert Hayen

Colloque GANIL

September 28 2023

LPC Caen

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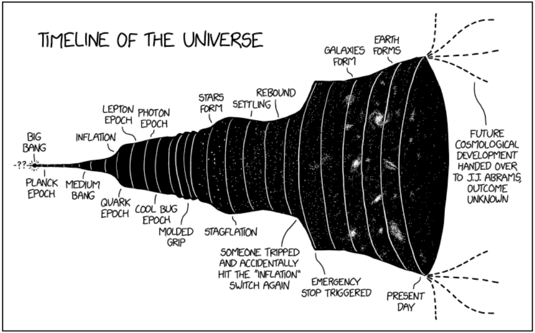
Fundamental symmetries & RIBs

Fundamental symmetries: *Precision measurements and symmetry tests of the Standard Model and Beyond*

Fundamental symmetries & RIBs

Fundamental symmetries*: Precision measurements and symmetry tests of the Standard Model and Beyond*

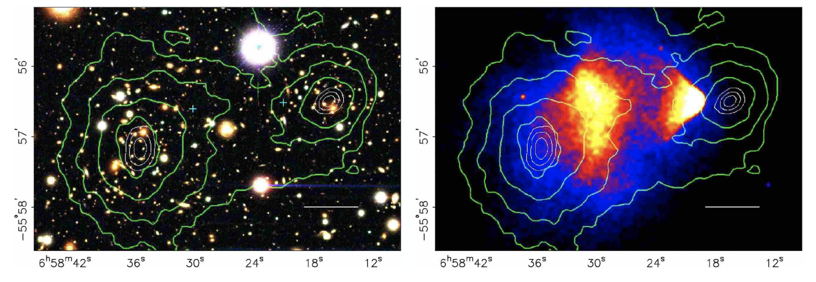


Extremely rich field with connections to

- Nature of neutrino's
- Dark matter
- Big bang nucleosynthesis
- Cosmology

Nature of dark matter

Visible matter $\neq$ gravitational mass



Good indications we're missing 80% of matter

Nature of neutrinos and mass mechanism

Neutrinos are all around, but elusive!

Image by Sandbox Studio

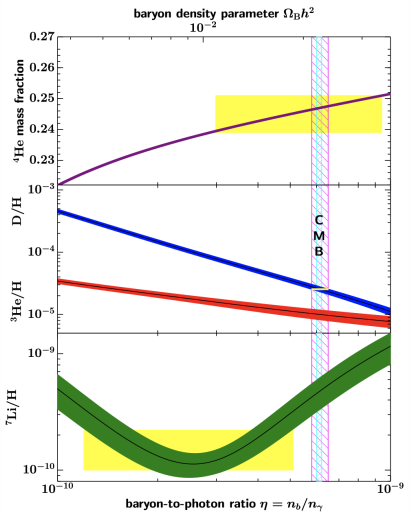
We don't know

- their mass
- how to give them mass
- own antiparticle?
- CP violation?

Baryogenesis

Why are we even here?

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = \mathcal{O}(10^{-10})$$



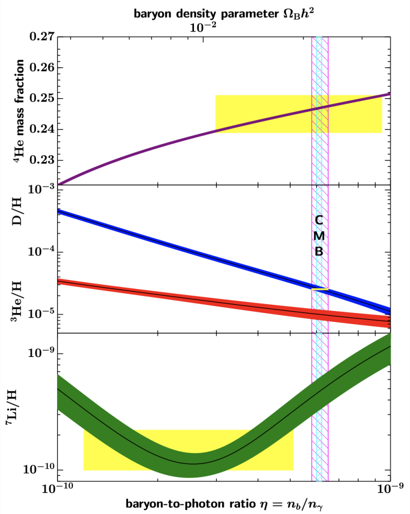
Baryogenesis

Why are we even here?

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = \mathcal{O}(10^{-10})$$

Naively,
Standard Model predicts **10-11 orders of magnitude smaller**

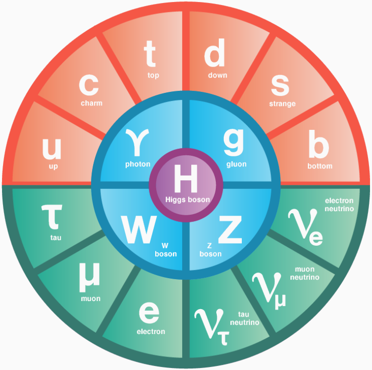
In more detail, it's simply impossible (Higgs is too heavy)



Meet the Standard Model

Three out of four
fundamental forces (no gravity):

Standard Model



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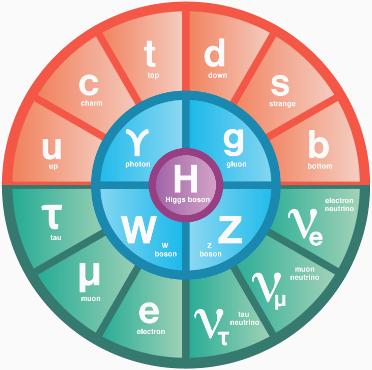

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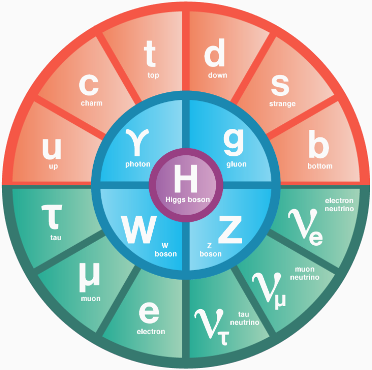
Great (annoyingly so), consistent with constraints at $\sim 10^{0-2}$ TeV



Meet the Standard Model

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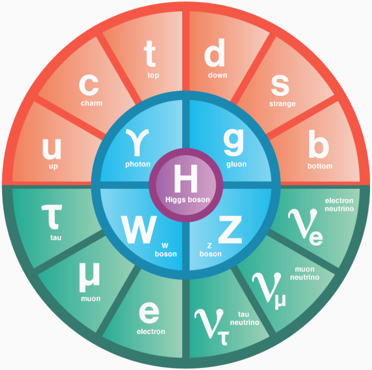
Open questions: dark matter, gravity, neutrino masses, ...



Introduction: Standard Model

What to do?

SM tests @ low energy: sensitive to off-shell exotic physics
(footprints rather than actual beast)

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Besides precision QED ($a_{e,\mu}, r_p, \ldots$), weak interactions probe

- (C)P violation
- CKM unitarity
- Lorentz structure

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All of these can be probed using **(nuclear)** β **decay** with RIBs!

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- (C)P violation Today
- CKM unitarity
- Lorentz structure Today

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β decay introduction

Require Lorentz invariance, get Lee-Yang Hamiltonian (SM: $V - A$)

$$\mathcal{H}_\beta = \sum_{i=V,A,S,P,T} \bar{p}\mathcal{O}_i n \times \bar{e}\mathcal{O}_i(C_i + C_i'\gamma^5)\nu_e$$

β decay introduction

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Differential decay rate

$$\Gamma \propto 1 + b\frac{m_e}{E_e} + a_{\beta\nu}\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_\nu}{E_e E_\nu} + \frac{\langle \boldsymbol{J} \rangle}{J} \cdot \left[A\frac{\boldsymbol{p}_e}{E_e} + B\frac{\boldsymbol{p}_\nu}{E_\nu} + D\frac{\boldsymbol{p}_e \times \boldsymbol{p}_\nu}{E_e E_\nu}\right]$$

$+$ higher order

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Baryon asymmetry

Already discussed baryon asymmetry:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = \mathcal{O}(10^{-10})$$

Baryon asymmetry

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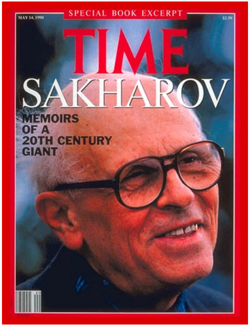
$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = \mathcal{O}(10^{-10})$$

Baryon asymmetry can arise **dynamically** on three conditions (Sakharov 1967)

- B-number violation
- CP violation
- Departure from equilibrium

First two present in SM but way too little,

Higgs too heavy for last



CP violation searches with MORA

$$\Gamma \propto 1 + b\frac{m_e}{E_e} + a_{\beta\nu}\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_\nu}{E_e E_\nu} + \frac{\langle \boldsymbol{J} \rangle}{J} \cdot \left[A\frac{\boldsymbol{p}_e}{E_e} + B\frac{\boldsymbol{p}_\nu}{E_\nu} + D\frac{\boldsymbol{p}_e \times \boldsymbol{p}_\nu}{E_e E_\nu} \right]$$

D term is T-odd, non-zero when $\mathrm{Im}(C_i) \neq 0$

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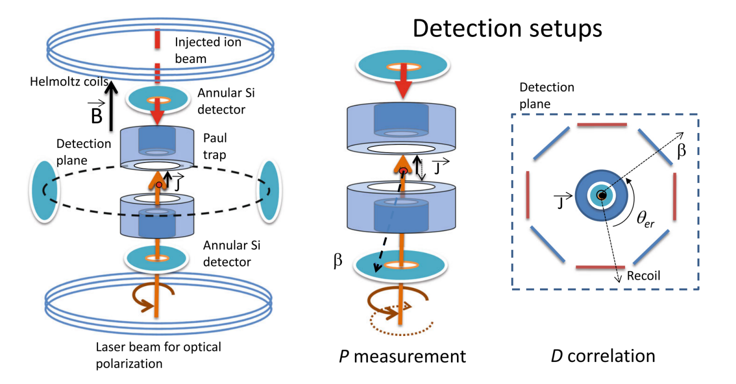

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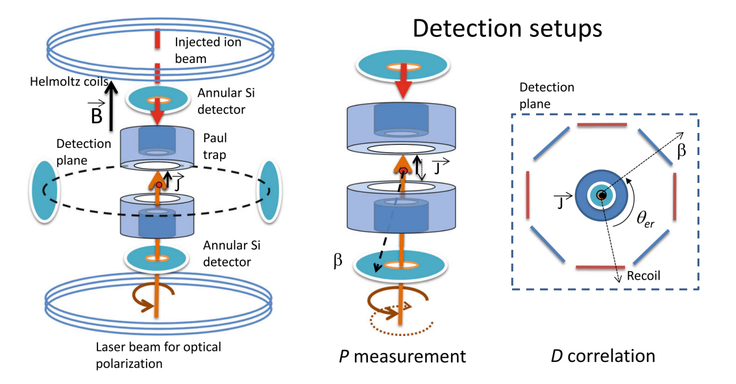

Currently at JYU, coming to DESIR. Talk by L.M. Motilla Martinez

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Fierz interference: Spectrum shape

Allowing exotic interactions (C_S, C_T) modifies β spectrum

$$P(E_e) = \text{Standard Model} \times \left(1 + b_F \frac{m_e}{E_e}\right)$$

Fierz interference: Spectrum shape

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Fierz interference

$$b_F \propto \text{Re}\left[|M_F|^2(C_S C_V^* + C_S' C_V'^*) + |M_{GT}|^2(C_T C_A^* + C_T' C_A'^*)\right]$$

Fierz interference: Spectrum shape

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Promising to directly measure spectra, but also tricky

- Detector linearity, energy losses, pile-up,...
- Theory spectrum calculation

See also talks by M. Kanafani, M. Lejoubioux

Naviliat-Cuncic, Gonzalez-Alonso PRC 94, 035503

LH *et al.*, RMP 90 015008

Mirror experimental status

Community is investi(gati)ng in different ideas

^{6}He-CRES

SALER

with new spectroscopy techniques & traps

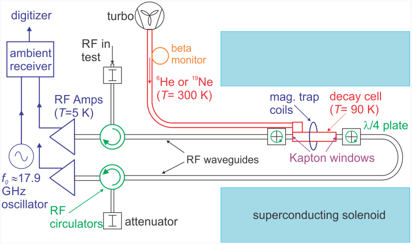
with additional great progress in the $A = 8$ system

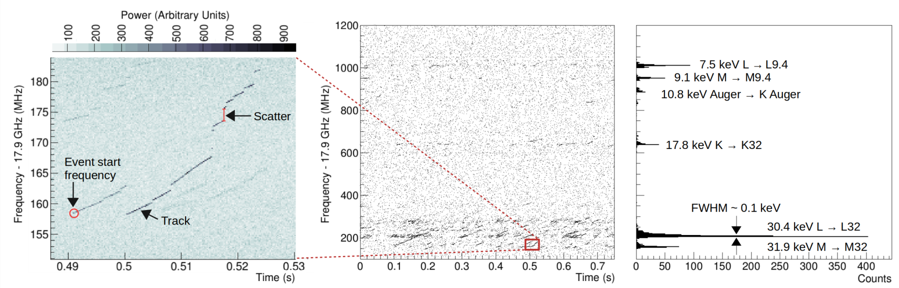
New technology: CRES

Cyclotron Radiation Emission Spectroscopy

$$f = \frac{|q|}{2\pi} \frac{B}{m_e + E_{kin}}$$

^{6}He and ^{19}Ne

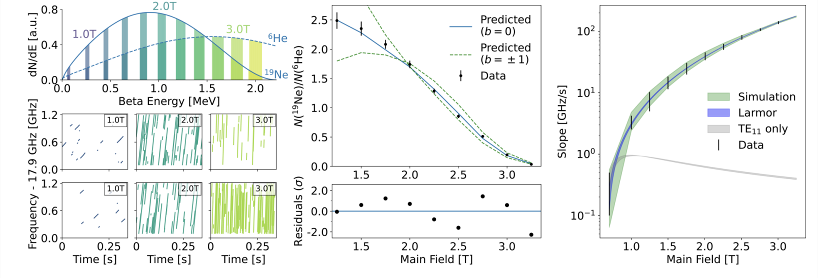




Physical Review Letters 131 (2023), 082502

New technology: CRES

Use ratio method: ^{6}He and ^{19}Ne have opposite b_F sign



Ratio means many systematic effects cancel to first order

Physical Review Letters 131 (2023), 082502

Investigating coupling to ion trap

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β recoil spectroscopy

Spectroscopy experiments currently focused on β (e^-/e^+), but extremely demanding

- Detector linearity, energy losses, pile-up,…
- Theory spectrum calculation

Naviliat-Cuncic, Gonzalez-Alonso PRC 94, 035503; LH *et al.*, RMP 90 015008

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Naviliat-Cuncic, Gonzalez-Alonso PRC 94, 035503; LH *et al.*, RMP 90 015008

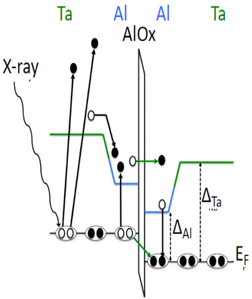
Instead, recoil spectroscopy has interesting features

- Compressed energy range ($<$keV instead of $\sim$ MeV)
- Electron capture gives single recoil peak
- Sensitive to β-ν correlation for $\beta^{\pm}$ decay

Meet superconducting tunnel junctions

- Two electrodes separated by a thin insulating tunnel barrier
- Superconducting energy gap Δ is of order ~meV
  → High Energy Resolution (~1 eV)
- Timing resolution on the order of 10 μs, making it among the fastest high-resolution quantum sensors available
  → "High" Rate (10^4 s^{-1} per pixel)

↖ *Ideal for RIB experiments at ISAC*



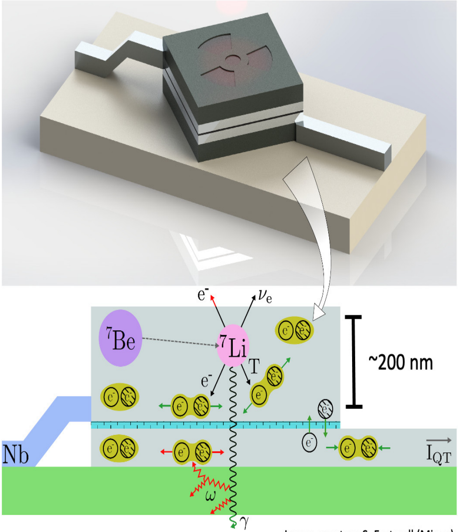
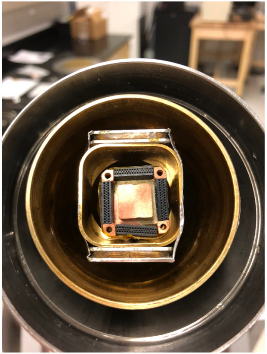
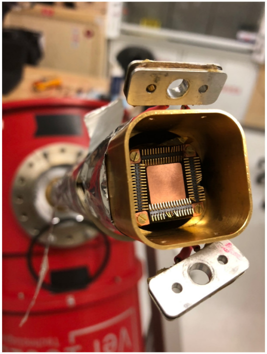
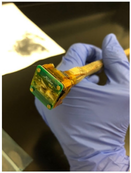


Image courtesy S. Fretwell (Mines)

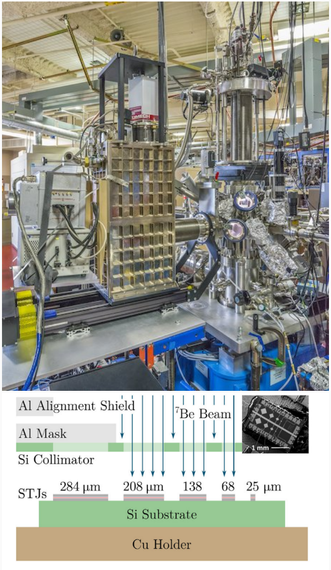
Superconducting tunnel junctions







BeEST@TRIUMF



^{7}Be electron capture

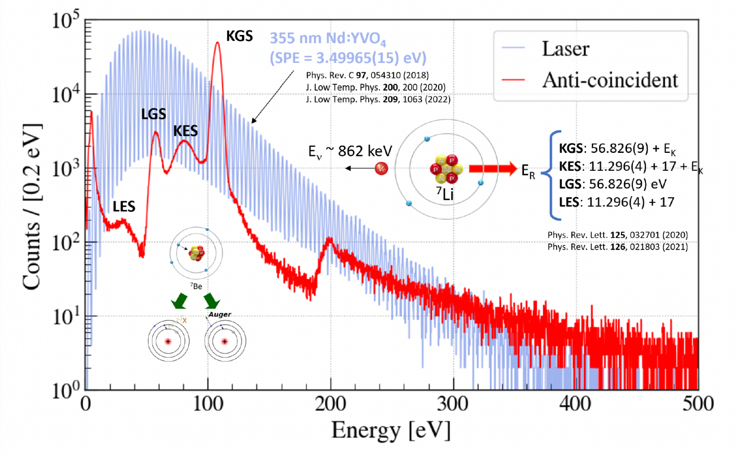
- Responsible for ^{7}Li creation in stars
- Essential contribution to solar neutrino spectrum

Measurement campaign

1. Implantation at ISAC (TRIUMF)
2. Ship to LLNL
3. Cool down and measure

BeEST@TRIUMF

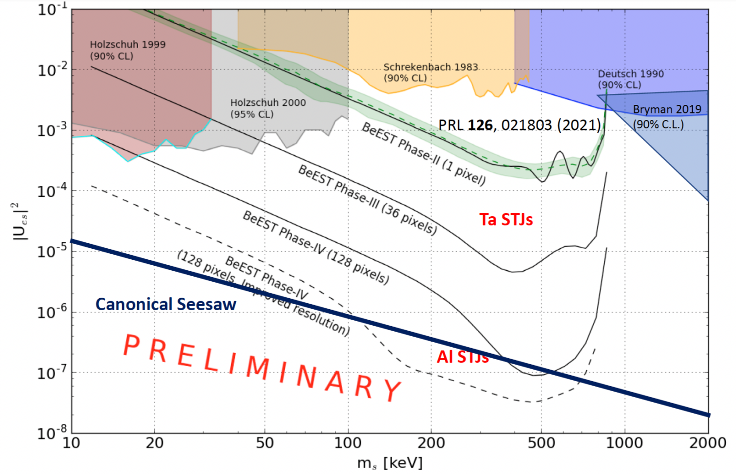
Most precise ^{7}Be L/K capture measurement



Constraints on MeV-scale sterile neutrino's

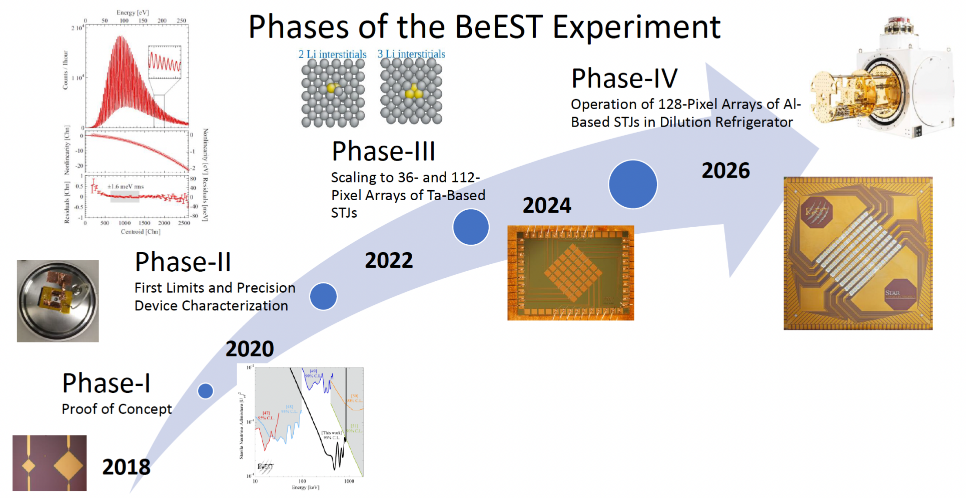
PRL 126 (2021) 021803; PRL 125 (2020), 032701

BeEST sterile neutrino limits



Phase I already into new territory

BeEST up to phase IV



STJ at RIBs

Can we do the same thing at radioactive ion beam facilities?

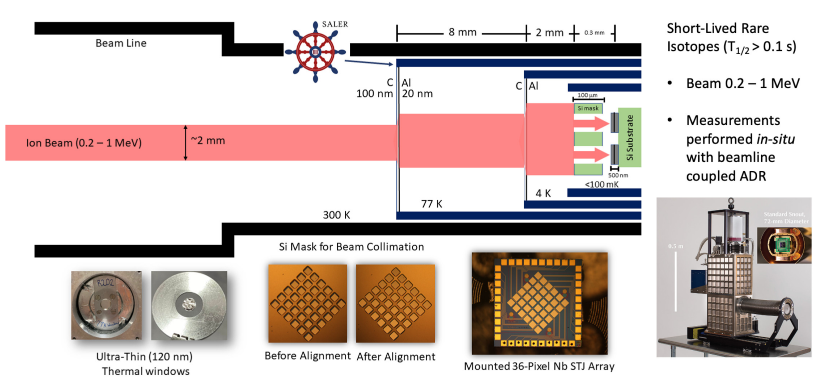
Introducing

SALER

Superconducting Array for Low Energy Radiation

Superconducting tunnel junctions

Concept to couple to beam line



Portability allows easy installation (ISAC, SPIRAL2, FRIB, ISOLDE, . . .)

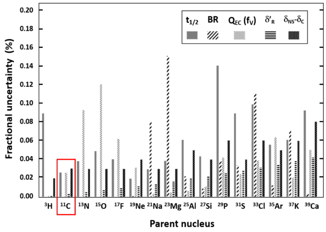
SALER@FRIB

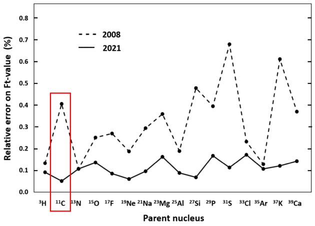
Commissioning in Fall 2023 at FRIB

Detector array will arrive late October!

SALER plans

^{11}C first physics target (long $t_{1/2}$, unreachable with traps!)





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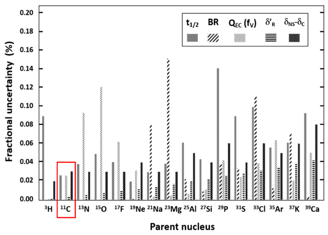
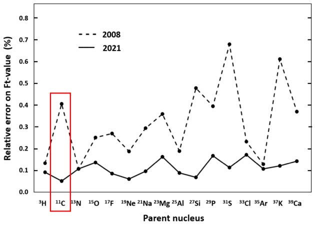
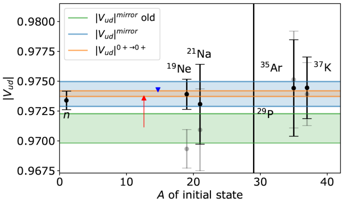
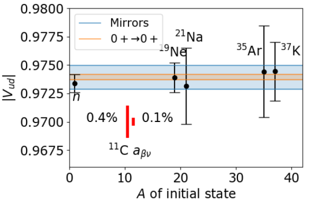




Excellent V_{ud} sensitivity





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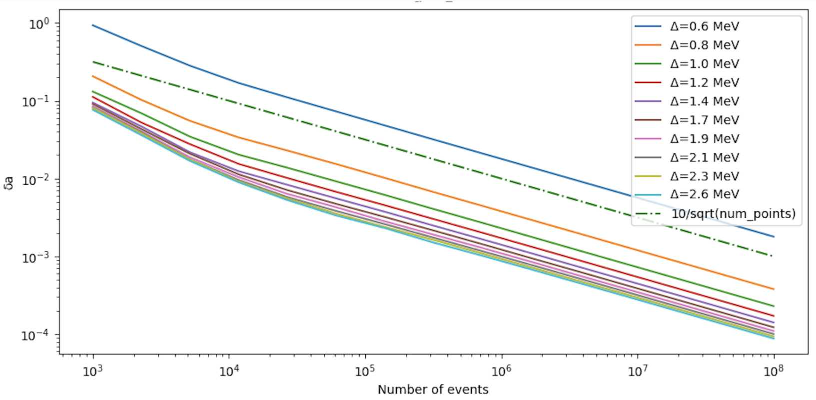
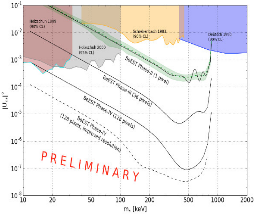
Statistical sensitivity (Preliminary!)

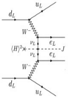


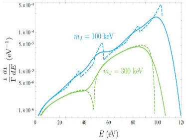
1E8 events ($\sim$ 1 day) statistical sensitivity $\delta V_{ud} \approx 3.7 \times 10^{-4}$

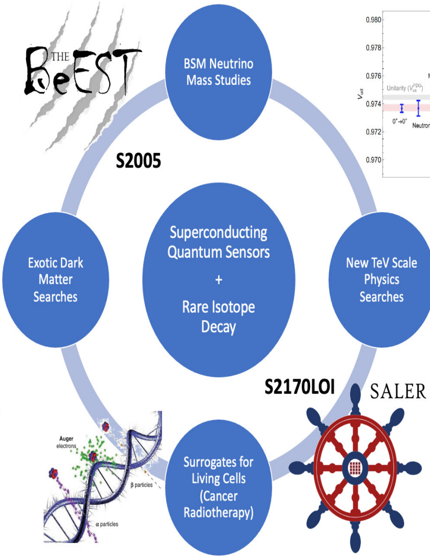
(Full superallowed data set is 3.2×10^{-4})

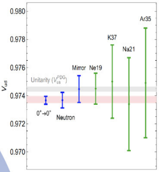
Superconducting tunnel junctions

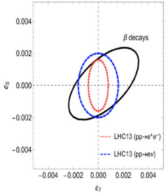


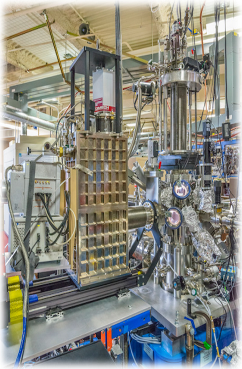












S. Fretwell *et al*, PRL **125**, 032701 (2020)
S. Friedrich *et al*, JLTP **200**, 200 (2020)
S. Friedrich *et al.*, PRL **126**, 021803 (2021)
K.G. Leach *et al*, arXiv:2112.02029 (2021)

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MORA collaborators:

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GSI

Z.Ge

RÉGION NORMANDIE · ANR · CNRS · ENSI CAEN · UNICAEN Université Caen Normandie · Normandie Université

BeEST & SALER

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

TRIUMF

NOVA
NOVA SCHOOL OF SCIENCE & TECHNOLOGY

THE BeEST

Lawrence Livermore National Laboratory

STAR CRYOELECTRONICS

NC STATE UNIVERSITY

COLORADO SCHOOL OF MINES
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FRIB

tpc caen

SALER

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NC STATE UNIVERSITY

Lawrence Livermore National Laboratory

U.S. DEPARTMENT OF ENERGY | Office of Science

Summary & Outlook

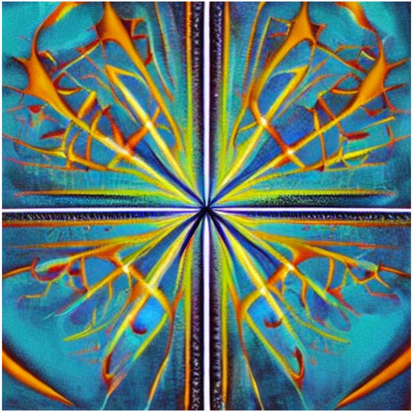
Fundamental symmetries lives at the interface, connections to many different fields

Nuclear β decay searches provide crucial input through variety of experiments, haven't even talked about

- Neutrino mass measurements
- Dark matter searches
- Big bang nucleosynthesis
- ...

Quantum sensing in β spectroscopy incoming, highly promising!

Thank you!



β decay symmetries according to Stable Diffusion

Introduction: Weak interaction & CKM matrix

Cabibbo-Kobayashi-Maskawa matrix relates weak and mass eigenstates

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix}_w = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_m$$

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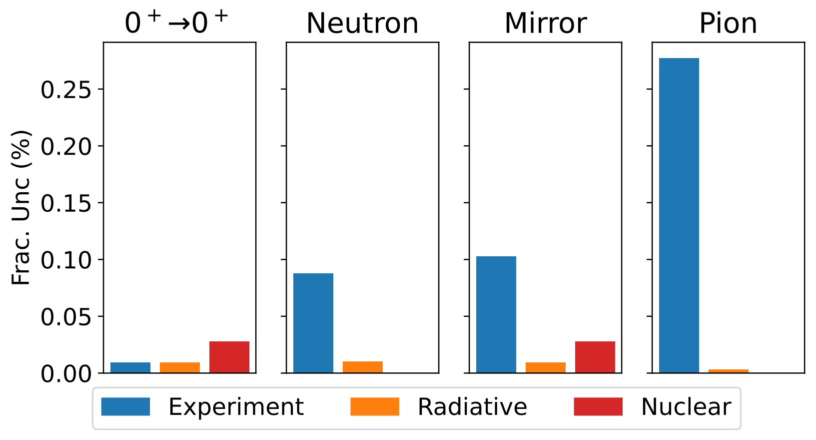
(nuclear) β decay, meson decay (π, K), $|V_{ub}|^2 \sim 10^{-5}$

Violations are sensitive to **TeV scale** new physics!

CKM unitarity: V_{ud} precision

Four ($\sim$)competitive channels of extracting V_{ud}



Status of $0^+ \to 0^+$ **great nuclear structure triumph**

2018-2020 reanalysis nuclear structure current bottleneck

CKM unitarity: Current status

Signs of non-unitarity at few σ level...

Disagreement between $Kl2$ and $Kl3$ $|V_{us}|$ 'Cabibbo angle anomaly'